

THERMAL SURFACE HARDENING TREATMENT OF STEELS

R. PRASAD

Scientist, National Metallurgical Laboratory, Jamshedpur

1. INTRODUCTION

Heat treatment of steels involves three steps :

- (i) Austenitization (Heating to austenite phase field),
- (ii) Quenching (Rapid cooling to form hard martensite), and
- (iii) Tempering (Heating below the eutectoid temperature to enhance toughness).

Steps (i) and (iii) involve heating. Usually this is done in conventional furnaces. However, when only the surface or local areas of a workpiece need to be hardened then furnace heating is not suitable. For such applications special heating techniques have been employed. Flame and induction heating are two important techniques of this kind. In this presentation we will discuss these techniques in some detail. We will also mention some of the most recently developed techniques in this area such as laser beam and electron beam heating.

2. INDUCTION HARDENING

A time-varying magnetic field through a coil produces an electric current in the coil. This phenomenon is known as electromagnetic induction. The induced current known as eddy current, leads to the heating of the workpiece.

2.1. Design of an induction heating equipment

To design a suitable induction heating equipment for a particular application, several factors have to be considered. These will be discussed in this section.

2.1.1. Frequency of the alternating current

(i) *Skin effect:* Eddy current produced in a workpiece are most intense at its surface. As one moves into the workpiece away from the surface the strength of the current decreases rapidly. This effect is known as skin effect. The skin effect causes greater heating near the surface of the workpiece.

A parameter defined to characterize skin effect is skin depth, which is distance beneath the surface at which the strength of the current decreases to $1/e$ (e being the base of natural logarithm), i.e., about 37% of its value at the surface. The skin depth depends upon the frequency of the alternating current and resistivity and relative magnetic permeability of the material of the workpiece as follows :

$$d = 5000 \sqrt{\frac{\rho}{\mu f}}$$

Where d = skin depth in cm,
 μ = relative permeability,
 ρ = resistivity in Ω - cm,
 f = frequency in Hz.

Frequency dependence of skin depth is shown in Fig. 1. The most important point to note from this relationship is that higher the frequency, lower is the skin depth. The selection of frequency decides the skin depth and in turn the case depth of the final hardened workpiece. As a general rule-of-thumb the final case depth can be taken to be equal to about one-half of the skin depth.

(ii) *Efficiency* : Heating efficiency defined as the percentage of power input to the coil which appears in the workpiece by induction is another important factor determining the selection of frequency. It is found that efficiency is poor if the ratio of the workpiece diameter (for cylindrical specimens) to skin depth is below 4. This is not a problem for surface hardening as skin depth is usually a very small fraction of the diameter of the workpiece. However, if induction heating is being used for through hardening applications then this becomes an important consideration. For such applications one uses critical frequency, a frequency which gives the ratio of workpiece diameter to skin depth as 4. Relationship of heating efficiency to applied frequency is shown in Fig.2.

(iii) *Mechanical stability* : Mechanical stability of coil and workpiece is also a factor which may affect frequency selection. Two current carrying conductors experience a repulsive (currents flowing in the same direction) or attractive (currents flowing in the opposite direction) forces. In an induction heating equipment the induction coil carries the applied current and the workpiece carries the eddy current. Thus there are forces between the two. These forces may tend to displace the workpiece in the coil or even distort the coil if not adequately supported. The forces are higher at lower frequencies. Thus adequate provision has to be made to support the workpiece and coil against these forces. If the forces are too great to be tolerated it may be necessary to go to higher frequencies.

2.1.2. Power and power sources

Exact calculations of power requirement for induction heating for surface hardening applications are quite difficult. This is due to the several factors involved during the process such as radiation losses, losses due to conduction of heat to inner layers of the workpiece and losses in coupling (i.e. all power put in the coil does not transfer into the workpiece). Thus only a rough estimate can be made. For details of such estimations the reader is referred to books listed in bibliography.

Once frequency and power requirements are known one can select a suitable power source for the application. Among the common power sources available are the following :

- (i) *Line frequency System* : These do not require frequency conversion. But due to its low frequency it is generally not very useful for surface hardening applications.
- (ii) *Motor-generator system* : Line power runs a motor which in turn runs a generator to supply power at higher frequencies. Such systems were more common in the past. But now-a-days solid state systems are preferred due to their higher efficiencies. However, motor generator system require less maintenance.
- (iii) *Solid state systems*: Solid state generators are lower in cost and have higher efficiencies. These systems convert line supply (ac) to dc and then to ac at the required frequencies.
- (iv) *Radio frequency system* : These produce frequencies of the orders of 100 kHz or more and thus are useful for producing shallow cases.

Fig.3. shows the ranges of power and frequency for common types of generators.

2.1.3 Coil design

This is probably the most critical step in the design of an induction heating equipment. The major task is to design a coil that induces a current in the workpiece giving proper heating pattern at as great an efficiency as possible. The design of a coil is very specific to a particular application and depends to a large extent on experience. Some of the common designs are illustrated in Fig.4. The most commonly used coil is the solenoid coil for round bars. Solenoid coils can also be used for heating internal surfaces of a tubular part. For continuous heating of bars channel coils can be used. Noencircling coils can also be used for

round bars and shafts. In this case the shaft is rotated to obtain uniform heating of the entire surface. For flat surfaces it is common to use pancake coils. Most coils are made of copper tubings that are water-cooled during the operation.

Matching of the coil to generator: An induction coil also has to be matched to the generator to achieve the heating in required time and to realize the full power rating of the generator. A coil matched to its generator draws full rated current at the rated voltage and the generator operates at a power factor close to unity. Matching is usually achieved by changing the number of turns in the coil or by using a matching generator.

2.2. Some examples of induction heat treatment

2.2.1 Crankshafts

Induction hardening of crankshafts have following advantages:

- (i) only the portion that requires hardening is heated thus leaving rest of the shaft soft for easy machining and balancing.
- (ii) due to reduced heating time there is minimum distortion and scaling.
- (iii) properties of induction heated crankshafts are found to be superior to those produced by other methods.

2.2.2 Gears

Induction heating is very good for gears as it keeps distortion to a minimum. Small gears can be hardened by using solenoid coils that encircle the entire perimeter of the gear (Fig.5a). However, for large gears such designs will require very large capacity induction generators. Thus for large gears tooth-by-tooth technique is quite common. In this method each tooth is treated individually by using a coil large enough to encircle a single tooth (Fig.5b).

2.2.3. Rails

Only the top portions (heads) of the rails are subjected to high stresses and wear. Thus induction heating is a suitable technique to selectively harden the heads of the rails. Rails as rolled products have a hardness of about 250 HB (Brinell Hardness). Using a low frequency (1000 Hz) induction treatment a hardness pattern as shown in Fig.6 can be achieved.

3. FLAME HARDENING

In flame hardening heating is done by a high-temperature flame or high-velocity combustion product gases.

3.1. Methods of Flame Hardening

Depending on the relative motion of flame head and the workpiece, following four methods of flame hardening can be distinguished.

3.1.1. Stationary or Spot Method

In this method both the flame and the workpiece are stationary. One or more flame tips may be used depending upon the extent of the area to be hardened. Quenching is usually done by immersion.

3.1.2. Progressive Method

In this method the flame head (usually multiple-tip) traverses over the surface of the stationary workpiece. The quenching facility may be integrated with the flame head.

3.1.3. Spinning Method

Here usually the workpiece (or, in some cases the flame) is rotated. This method is adaptable to automation.

3.1.4. Progressive-spinning Method

This method combines the progressive and spinning methods - the workpiece rotates while the flames traverse the workpiece from one end to the other. Useful for long parts such as shafts and rolls.

3.2. Fuel Gases

For flame hardening applications neutral or slightly carburizing flame are used. If the flame is oxydizing it may lead to overheating and decarburization. Strongly carburizing flames may introduce unwanted carbon into the surface. Following is a list of common fuel gases used in flame hardening

- i) Acetylene
- ii) Natural Gas
- iii) Propane
- iv) Methylacetylene Propadiene (MAPP)

3.3. Burners

Design of burners depend upon whether oxygen or air is used to burn the fuel. We thus have two major types of burners.

3.3.1. Oxy-fuel Gas Flame Burners

Temperatures of oxy-fuel flames are generally much above those that are safe for treatment of metals. So these burners are designed to avoid direct heating of workpiece. Fig.7 shows the design of an oxy-fuel gas burner.

3.3.2. Air-fuel Gas Burners

There are two common types in this category :

- i) the radiant type burner : In this type of burner (Fig.8a) a refractory cup is heated with air-fuel flames. The hot cup then heats the workpiece by radiation.
- ii) the high-velocity convection burner : This is designed as a small refractory lined box (Fig.8b) in which air-fuel mixture is burnt heating the lining to almost theoretical flame temperatures. Hot gases at about 1600°C come out from restricted slots at high velocities of about 700 ms^{-1} and heat the workpiece.

3.4 Operating variables

Some of the important operating variables for the flame hardening process are listed below :

- i) Flame-to-work surface distance,
- ii) Flame velocity,
- iii) Oxygen-to-fuel ratio,
- iv) rate of travel of flame or workpiece.

4. SOME NEWER TECHNIQUES FOR SURFACE THERMAL TREATMENT OF STEELS

4.1 Laser Surface Treatment

Local surface regions can be selectively austenitized by absorption of heat from intense laser beams. As ferrous metals are not very good absorbers of heat from laser, special coatings (manganese phosphate, graphite or carbon black paint) are applied to the surface. Quenching of the austenitized region takes place by rapid conduction of

heat into cooler bulk material of the workpiece (a process known as self-quenching). Due to very rapid rates of cooling involved during self-quenching, even steels of lower hardenability can be treated by laser.

4.2 Electron Beam Heating

This is like laser treatment, but the source of heat is high energy electron beams. As electron are easily absorbed in the metals, no energy absorbing coatings are required. Like in laser treatment, self-quenching takes place to form martensite.

ACKNOWLEDGEMENTS

I wish to thank Prof. P. Ramachandra Rao for encouragement and Dr.A. Jordar for discussions and help in the preparation of this presentation.

BIBLIOGRAPHY

The contents of this presentation are based on the following two books where details and further references can be found :

1. Heat Treating, ASM Handbook, Volume 4, ASM International, Ohio, 1991.
2. S.L. Semiatin and D.E.Stutz, Induction Heat Treatment of Steels, ASM, Ohio, 1986.

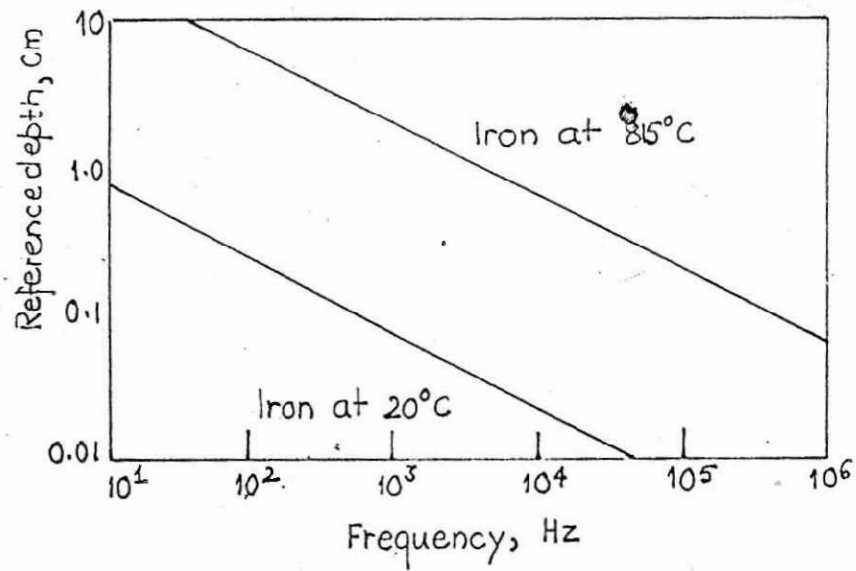


Figure -1 Skin depth as a function of frequency (after Semiatin and Stutz).

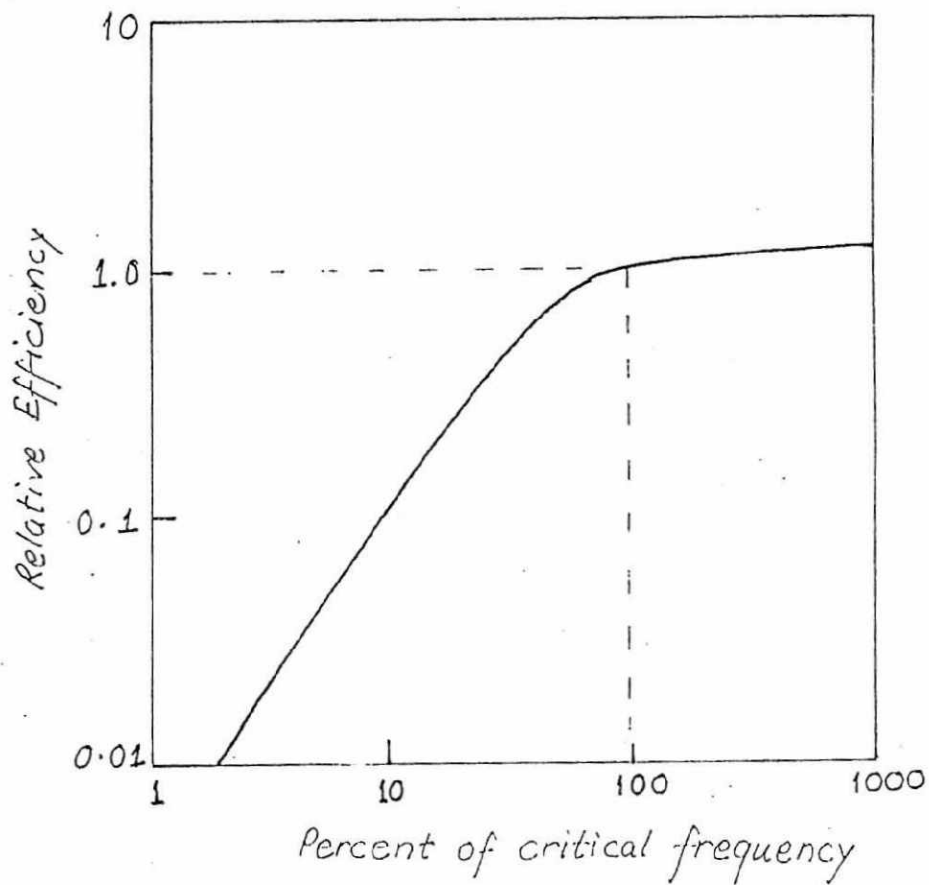


Figure-2 Heating efficiency as a function of frequency (after Semiatin and Stutz).

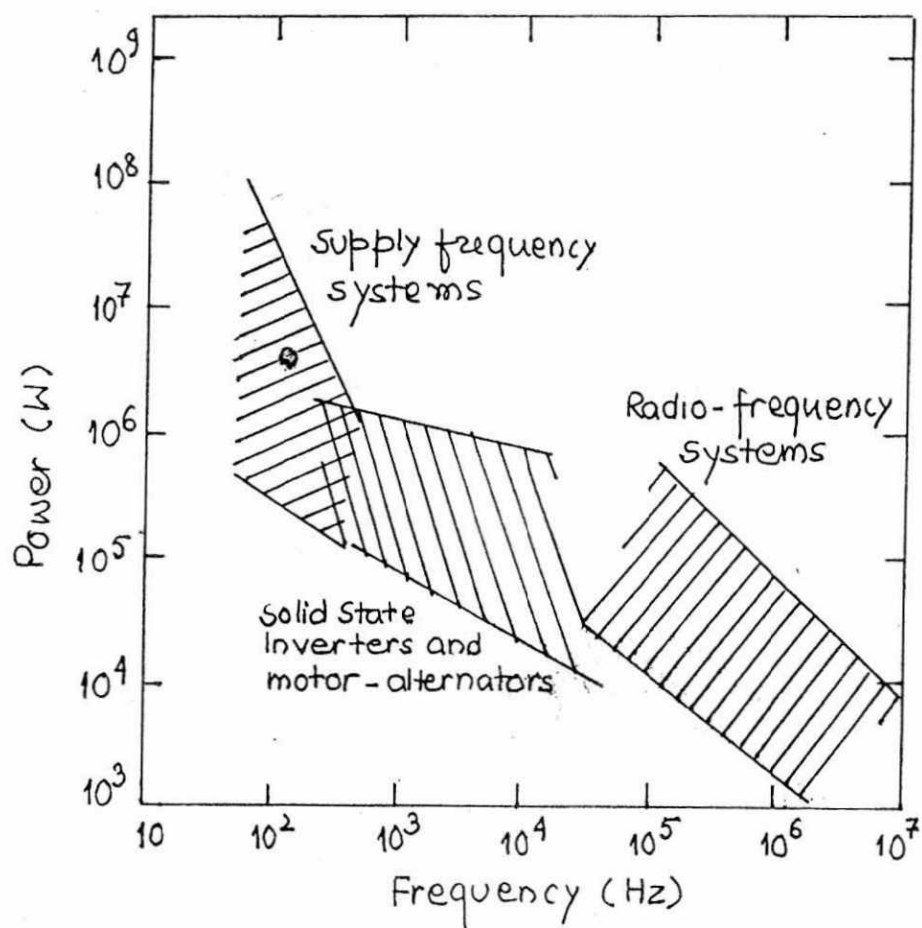


Figure-3 Power and frequency ranges for common type of induction heating generators (after Semiatin and Stutz).

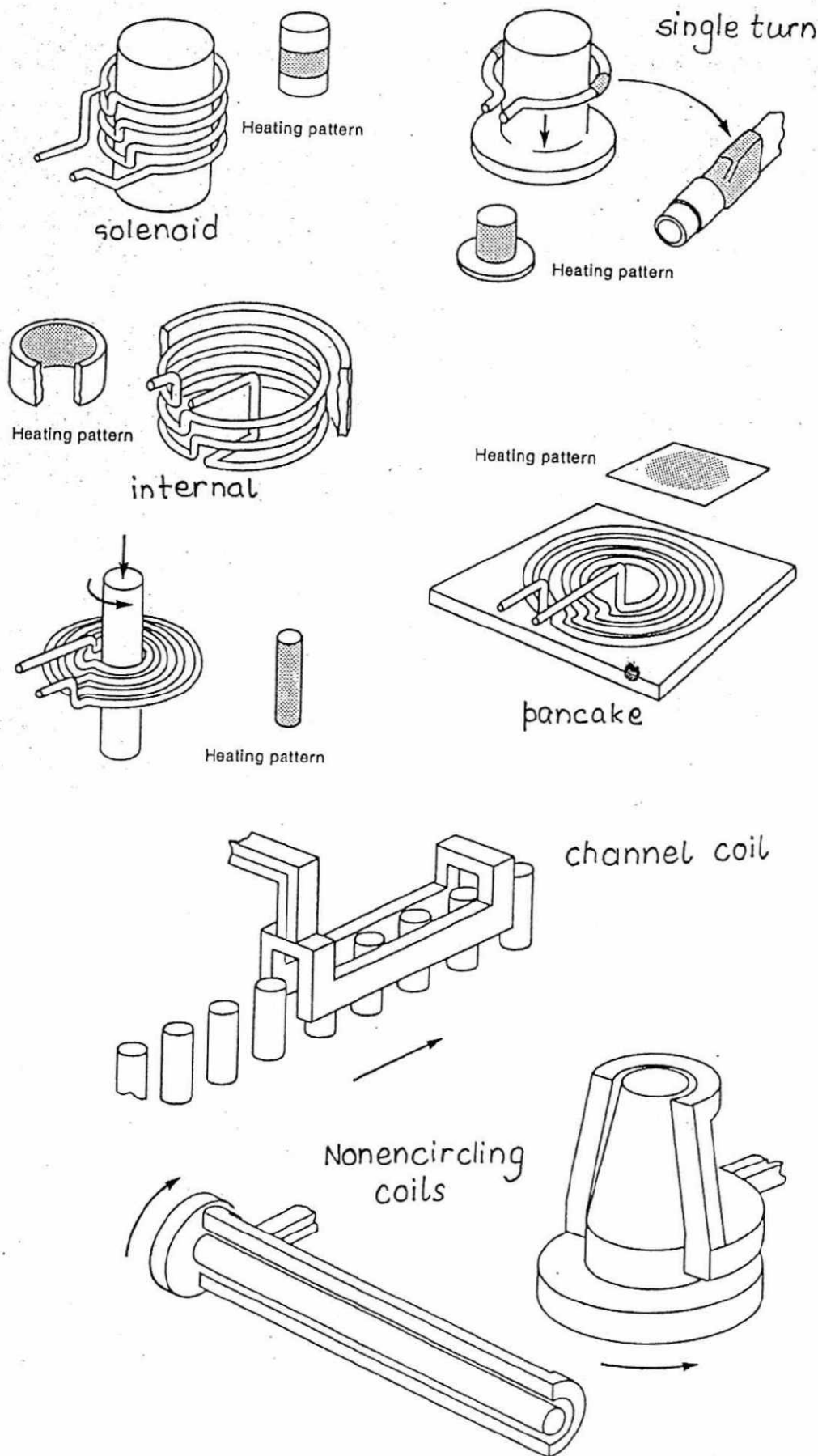


Figure-4 Some of the various coils used for induction heating applications (after Semiatin and Stutz).

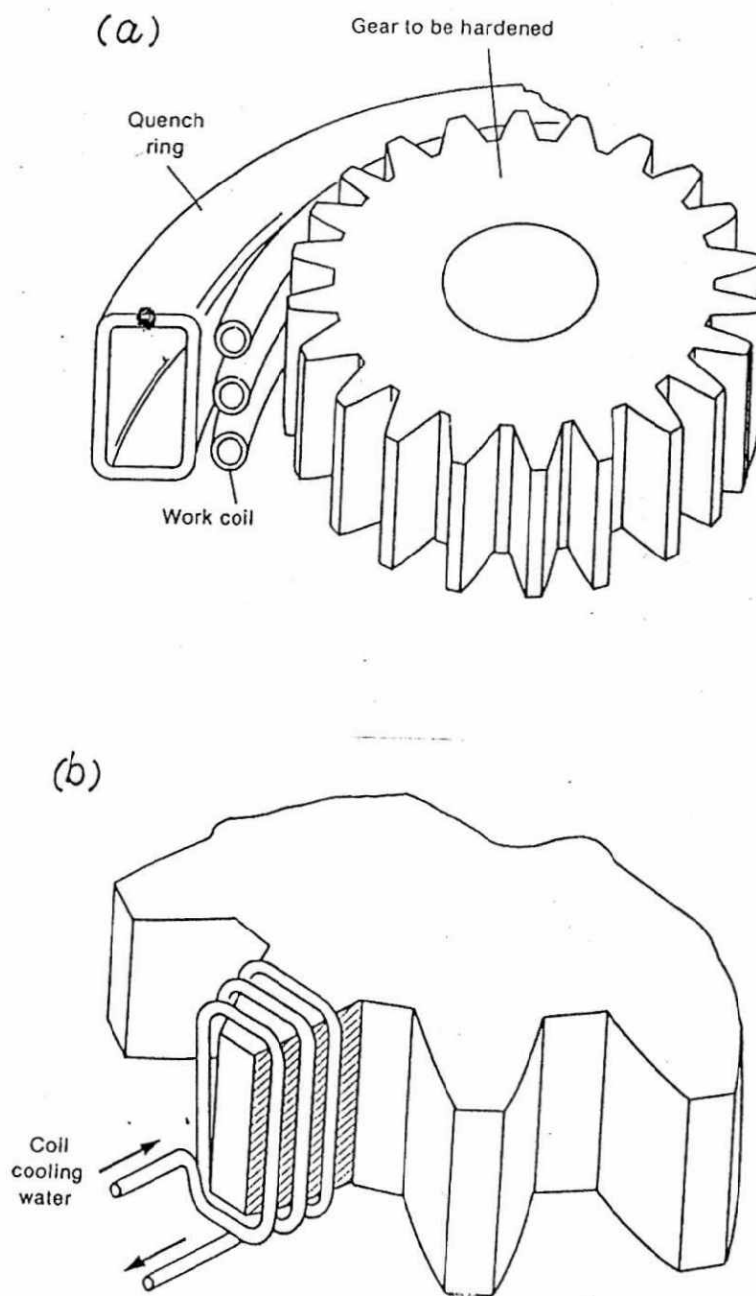


Figure-5 Induction heating of a gear : (a) Solenoid coil and concentric quench ring around a small gear; (b) coil for tooth-by-tooth hardening of a large gear. (after Semiatin and Stutz).

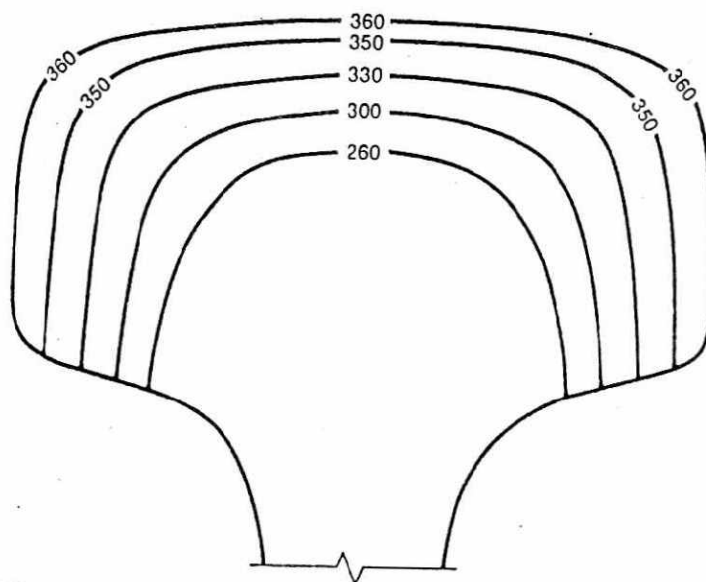


Figure-6 Hardness pattern of an induction hardened rail. Numbers indicate Brinell hardness (after Semiatin and Stutz).

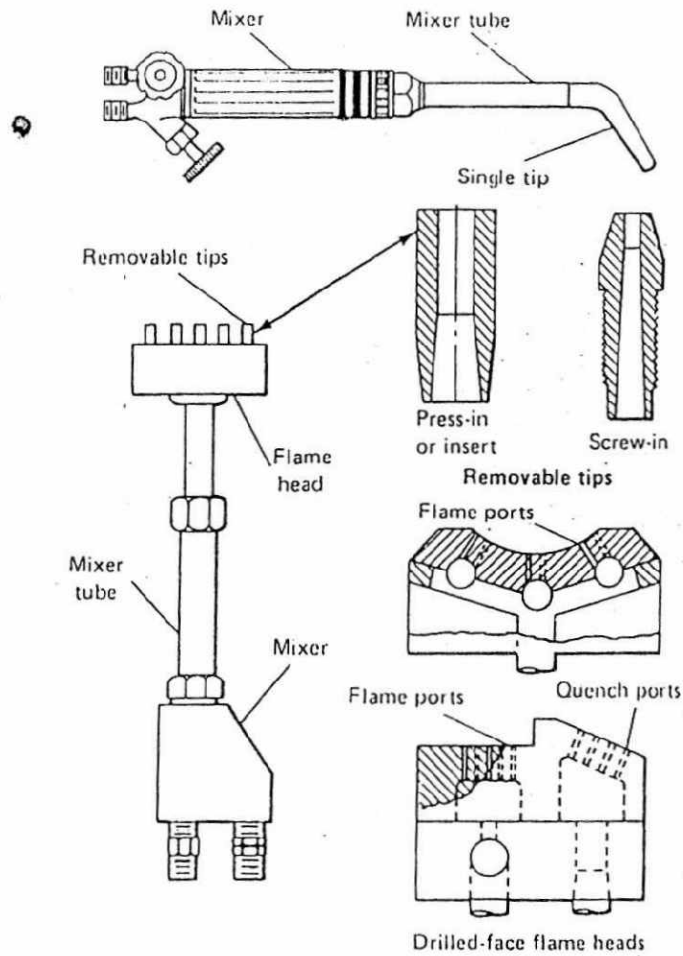


Figure-7 Design of an oxy-fuel gas burner (after ASM Handbook, Vol.4).

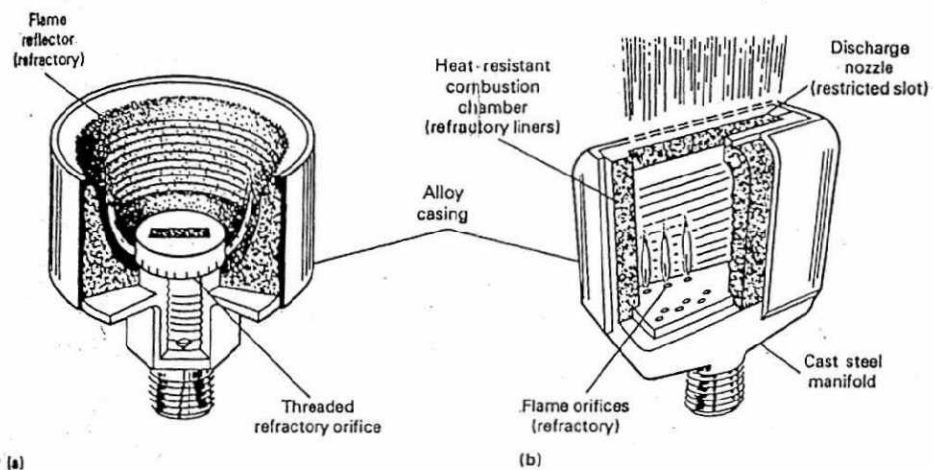


Figure-8 Air-fuel burners : (a) radiant burner (b) high-velocity convection burner (from ASM Handbook, Vol.4).